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Measurements of an anomalous global methane increase during 1998

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Abstract. Measurements of atmospheric methane from a globally distributed network of air sampling sites indicate that the globally averaged CH_4 growth rate increased from an average of 3.9 ppb yr^{-1} during 1995-1997 to 12.7 ± 0.6 ppb in 1998. The global growth rate then decreased to 2.6 ± 0.6 ppb during 1999, indicating that the large increase in 1998 was not a return to the larger growth rates observed during the late-1970s and early-1980s. The increased growth rate during 1998 corresponds to an increase in the imbalance between CH_4 sources and sinks equal to ~24 Tg CH_4, the largest perturbation observed in 16 years of measurements. We suggest that wetland and boreal biomass burning sources may have contributed to the anomaly. An adaptation of a global process-based model, which included soil-temperature and precipitation anomalies, was used to calculate emission anomalies of 11.6 Tg CH_4 from wetlands north of 30°N and 13 Tg CH_4 for tropical wetlands during 1998 compared to average emissions calculated for 1982-1993. For 1999, calculated wetland emission anomalies were negative for high northern latitudes and the tropics, contributing to the low growth rate observed in 1999. Also 1998 was a severe fire year in boreal regions where ~1.3×10^5 km^2 of forest and peat land burned releasing an estimated 5.7 Tg CH_4.

1. Introduction

Atmospheric methane (CH_4) is of considerable interest due to its importance as a greenhouse gas, the role it plays in tropospheric chemistry, and its role in terminating catalytic O_3 destruction cycles involving halogens in the stratosphere. Recent observations of relatively large interannual variations in CH_4 growth rate, superimposed upon a trend that has decreased monotonically for almost 20 years, may provide information to improve our understanding of methane's budget of sources and sinks.

Most variations in CH_4 growth rate have been related to natural events, for example the eruption of Mt. Pinatubo during 1991. When assessing interannual variations in CH_4 growth rate, it is often difficult to determine with certainty which of the possible sources or sinks were contributors. For example, *Dlugokencky et al.* [1996] showed that SO_2 emitted during the eruption of Pinatubo (and the subsequent sulfate aerosol) affected tropical photochemistry and caused larger CH_4 growth rates in the tropics during 1991. *Hogan and Harriss* [1994] attributed the decrease in CH_4 growth rate observed at high northern latitudes during 1992 to decreased emissions from northern wetlands due to low temperatures observed as a result of the eruption [*Dutton and Christy*, 1992], while *Bekki et al.* [1994] attributed this decrease to increased photochemical destruction of CH_4. It was also suggested that decreased methane emissions from the fossil fuel sector of the former Soviet Union, brought about by the collapse of the Soviet Union, contributed to the decreased CH_4 growth rate in 1992 [*Law and Nisbet*, 1996; *Dlugokencky et al.*, 1994a].

Here we present globally and zonally averaged CH_4 mole fractions and examine the large increase in CH_4 growth rate that was observed during 1998. We suggest that this increased growth rate was due, at least in part, to anomalously high temperatures and precipitation during 1998, which led to greater emissions from high northern latitude and tropical wetland regions. A second, smaller potential contributor was CH_4 emitted from boreal biomass burning, particularly from Siberia during late-summer, 1998.

2. Experimental Methods

Our main objective is to make high-precision measurements of the global distribution of atmospheric methane that can be used as a top-down constraint on the global CH_4 budget. The sampling and measurement details have been described elsewhere [*Dlugokencky et al.*, 1994b], so only a brief summary is given here. Samples are collected in duplicate, approximately weekly, from a globally distributed network of background air sampling sites (Figure 1) and analyzed in Boulder, Colorado. Methane is determined by gas chromatography with flame ionization detection. The relative precision of the measurements during the period 1991 to 1999 was ~0.1%. All measurements are reported in dry-air mole fraction (nmol mol^{-1}, abbreviated "ppb") relative to an internally-consistent standard gas scale. This scale is propagated from one cylinder to the next with an accuracy of 0±0.2 ppb (95% confidence limit). We are confident that the changes in CH_4 growth rate described here are not the result of measurement artifacts because of drifts or shifts in our standard scale [*Steele et al.*, 1992; *Dlugokencky et al.*, 1994b] or artifacts of our sample collection and storage methods. The measurements are edited for sampling and analytical problems and then selected for background conditions. These quality-control steps ensure that the measurements are representative of large well-mixed volumes of the tropospheric boundary layer. We include 43 time series, excluding mountain sites, those sites that are frequently affected by local-scale pollution, and sites with large gaps in their measurement records from this analysis. Data are available from the CMDL World Wide Web page (path: ftp://ftp.cmdl.noaa.gov/ccg/ch4/flask/).

Measurements are smoothed [*Dlugokencky et al.*, 1994b] to define an evenly spaced matrix of CH_4 mole fractions in the boundary layer as a function of time and latitude. The matrix is averaged to define global, hemispheric, semihemispheric (HNH = 30-90°N; LNH = 0-30°N; LSH = 0-30°S; and HSH = 30-90°S), and polar (PNH = 53-90°N) zonally averaged values.

Methane emission anomalies from boreal wetlands during 1998 were calculated using an adaptation of the global process-based model of *Walter* [1998]. Model CH_4 emission rates and soil

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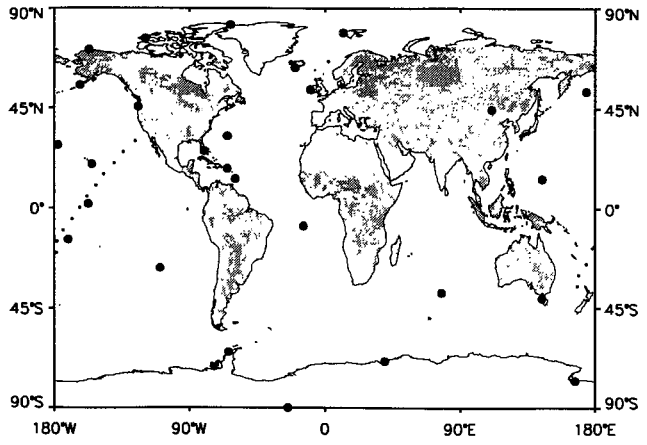

Figure 1. Locations of sites in the NOAA CMDL cooperative air sampling network used in this study (circles). Some sites were not active for the entire period (1984-1999). Large circles are "fixed" sites, and small circles are approximate samplings locations along ship's cruise tracks. The gray-shaded areas identify wetland regions [based on *Matthews and Fung*, 1987].

concentration profiles were tested against six comprehensive data sets from different wetlands. Observation periods ranged from one season to 3 years [*Walter and Heimann*, 2000; *Walter*, 1998]. The adaptation used to calculate anomalies is a multiple linear regression between inputs (soil-temperature and precipitation anomalies) and output (CH_4 emission anomalies) in a 12-year run (1982-1993) of the global process-based model. This regression model uses National Centers for Environmental Prediction soil temperature (0-10 cm depth) and precipitation anomalies calculated relative to the 1980-1999 climatology. Wetland distribution and environmental characteristics were from *Matthews and Fung* [1987] (see Figure 1 for wetland distribution).

3. Results and Discussion

3.1. Methane Observations

Globally averaged CH_4 mole fractions, deseasonalized trend line, and instantaneous growth rate (time-derivative of the trend) are plotted in Figure 2. The increase in CH_4 global growth rate during 1998 is one of a series of variations superimposed on a long-term decrease in growth rate. The observed long-term decrease in growth rate is consistent with constant CH_4 emissions and lifetime in a system approaching chemical steady state [*Francey et al.*, 1999; *Etheridge et al.*, 1998; *Dlugokencky et al.*, 1998] or with increasing emissions that, in part, balance a decreasing CH_4 lifetime [*Krol et al.*, 1998; *Karlsdóttir and Isaksen*, 2000]. Annual increases in CH_4 (in ppb) by latitude zone were determined from the trend line as the difference in CH_4 mole fraction from the beginning to the end of each year (1984-1999), and these are summarized in Table 1. Also included in Table 1 are "predicted" annual increases based on the assumption that total CH_4 emissions and [OH] were approximately constant during 1984-1999. The increase in globally averaged CH_4 during 1998 was 12.7 ± 0.6 ppb (uncertainty is 1σ); this represents an imbalance between sources and sinks of 35 Tg CH_4 (based on the conversion factor in *Fung et al.* [1991] and where 1 Tg = 10^{12} g). Relative to the long-term trend, the increase during 1998 is the largest variation in our record. The average rate of increase in methane during the 3 years prior to 1998 was 3.9 ppb yr^{-1} or an increase of 11 Tg CH_4 yr^{-1} in the global CH_4 burden; for 1998, this corresponds to an anomaly in the difference between emissions and sinks of 24 Tg CH_4. Using the "predict" column in Table 1, the increase in 1998 would be 23 Tg CH_4.

For the semihemispheres (each representing 25% of the global atmosphere), the largest growth rate during 1998 was observed in the high northern latitudes (30-90°N) at 15.2 ± 1.2 ppb. At finer spatial resolution, the 1998 increase for the northern-most 10% of the atmosphere (53-90°N), was 17.2 ± 0.8 ppb. In the southern hemisphere, the CH_4 increase at low latitudes (0-30°S) was 14.0 ± 0.8 ppb. During 1999, the global increase was 2.6 ± 0.6 ppb, comparable to values observed in the 3 years prior to 1998 (1999 values are preliminary). A slight decrease in CH_4 mole fraction was observed in the northern hemisphere during 1999 (-1.6 ± 1.1 ppb). This low growth rate is, in part, due to mixing of "excess" CH_4 to the southern hemisphere and to higher altitudes, but it also suggests that there has not been a return to larger growth rates observed in the late-1970s and early-1980s.

3.2. Possible Reasons for Increased Growth Rate

The warmest year on record is 1998 [*Hansen et al.*, 1999]. This suggests that a change in emissions from a source with temperature-dependent emission rates, such as natural wetlands, possibly contributed to the increased growth rate. We tested this idea with the model, where CH_4 emission rates from natural wetlands increase by ~20% for a 1°C increase, nearly independently of the location of the temperature anomaly. Emission rates in the model also depend on soil moisture, increasing by 8% globally for a 20% increase in precipitation, but

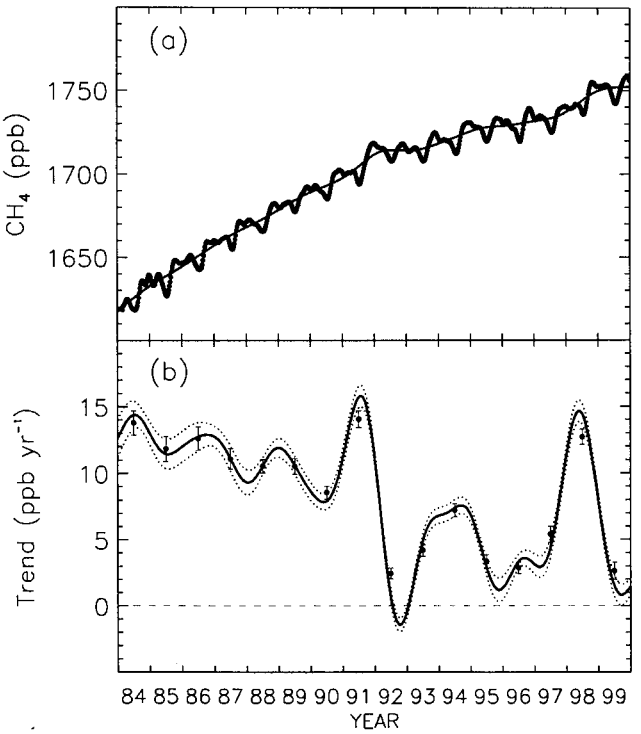

Figure 2. (a) Globally averaged CH_4 mole fractions. Solid line is the deseasonalized trend. (b) Globally averaged instantaneous growth rate determined as the time-derivative of the trend line in (a). Symbols are global annual increases in Table 1. Uncertainties are ±1σ determined with a nonparametric statistical technique [*Steele et al.*, 1992].

Table 1. Annual Increases in Atmospheric CH_4 by Latitude Zone (ppb)

	Latitude Zone							
Year	30-90°S	0-30°S	0-30°N	30-90°N	0-90°S	0-90°N	Global	Predict*
1984	11.9±0.8	14.4±0.5	11.7±2.3	17.2±2.2	13.1±0.5	14.4±1.6	13.8±0.9	14.5
1985	11.9±0.6	11.2±0.4	13.9±2.3	10.3±2.6	11.6±0.4	12.1±1.7	11.8±0.9	13.3
1986	12.0±0.7	10.2±1.0	13.9±1.9	14.3±1.5	11.1±0.7	14.1±1.4	12.6±0.9	12.2
1987	9.8±0.4	9.1±0.7	11.0±1.6	14.4±1.9	9.5±0.4	12.7±1.4	11.1±0.8	11.2
1988	12.7±0.3	15.4±0.8	7.4±1.2	6.7±1.2	14.0±0.4	7.0±0.8	10.5±0.5	10.3
1989	11.4±0.7	8.6±0.7	11.9±1.1	10.2±1.3	10.0±0.6	11.1±1.0	10.5±0.6	9.5
1990	6.3±0.9	7.0±0.6	10.1±1.1	10.9±1.0	6.6±0.5	10.5±0.7	8.6±0.5	8.7
1991	15.8±0.7	15.1±0.4	15.4±1.4	10.0±1.5	15.4±0.4	12.7±1.1	14.1±0.6	7.9
1992	6.4±0.3	4.0±0.4	-0.7±1.0	0.1±1.1	5.2±0.2	-0.3±0.8	2.5±0.4	7.3
1993	0.3±0.7	3.2±0.4	6.1±1.0	7.3±0.8	1.7±0.4	6.7±0.7	4.2±0.4	6.7
1994	7.7±0.5	8.2±0.3	7.7±1.6	5.2±0.9	8.0±0.3	6.5±1.0	7.2±0.5	6.1
1995	4.4±1.0	4.6±0.4	1.5±1.5	2.9±0.8	4.5±0.6	2.2±0.9	3.3±0.5	5.6
1996	3.0±0.8	2.4±0.5	4.3±0.9	1.9±0.7	2.7±0.5	3.1±0.6	2.9±0.4	5.2
1997	6.4±0.4	3.3±0.6	6.7±2.0	5.1±1.2	4.9±0.3	5.9±1.1	5.4±0.6	4.7
1998	11.1±0.2	14.0±0.8	10.5±1.8	15.2±1.2	12.6±0.4	12.8±1.1	12.7±0.6	4.3
1999	7.2±0.7	6.6±0.4	0.0±1.0	-3.2±2.0	6.9±0.4	-1.6±1.1	2.6±0.6	4.0

Uncertainties are ±1σ determined with a nonparametric statistical technique [*Steele et al.*, 1992].
*Predicted global increase based on constant CH_4 emissions and lifetime [*Dlugokencky et al.*, 1998].

the magnitude of the emission anomaly depends on the location of the precipitation anomaly. Temperature and precipitation anomalies, calculated for 1998 and 1999 (relative to 1980-1999) for wetland regions, are summarized in Table 2 by latitude zone. Positive temperature and precipitation anomalies were observed in the HNH and the LSH during 1998, but in the LNH, only the temperature anomaly was positive. CH_4 emission anomalies, calculated with the model relative to the average for 1982-1993, are summarized by semihemisphere for 1998 and 1999 in Table 3. The emission anomalies were +11.6 Tg CH_4 for northern wetlands (>30°N) during 1998 and +11.5 Tg CH_4 for southern tropical wetlands. There is good qualitative agreement between model-calculated anomalies and the spatial patterns in observed growth rate; the largest increases in 1998 were observed in the HNH and LSH.

Temporal behavior in the HNH observations is also suggestive of a wetland source. Annual methane increases for 1997-1998 (e.g., May 1997 to May 1998) were 6-10 ppb for January through May, but rapidly increased from June through November to a maximum 24 ppb. In the HNH, wetlands are the only seasonal source large enough to cause such a large change in growth rate.

The total anomaly calculated for wetland emissions in 1998 (24.6 Tg CH_4) is in good agreement with the observed anomaly, but this must be viewed with caution. Global wetland emissions from the model are ~40% larger than other current estimates (e.g., *Fung et al.* [1991]), so it is likely that calculated wetland emission anomalies are also overestimated by up to 40%. The model does not, however, allow for expansion of wetlands because of increased precipitation or melting of permafrost in warm, wet years such as 1998. Importantly, both observations and model suggest strong positive emission anomalies during 1998, and the spatial and seasonal patterns of the anomalies predicted by the model, which we have much higher confidence in than the magnitude of the anomaly, are in good agreement with the observed spatial and seasonal patterns of increased growth rate.

A second possible additional source of CH_4 was from biomass burning in boreal regions. *Kasischke et al.* [1999] found that, from 1970-1999, about 80% were light fire years where ~0.7 Tg CH_4 were released from boreal regions. The remaining years, including 1998, were severe fire years. During 1998, ~8.5×10^4 km^2 burned in Russia; ~6×10^4 km^2 burned after August 1 in the Russian Far East, and the remaining 2.5×10^4 km^2 was distributed throughout the summer fire season (May 1 to October 15). In Canada ~4.5×10^4 km^2 burned, for a total of ~13×10^4 km^2 that burned in boreal regions during 1998. Methane emissions from the 1998 fires were estimated to be in the range of 3.9 to 6.3 Tg CH_4 depending on the characteristics of the fire and types of vegetation burned with a best estimate of 5.7 Tg CH_4 because of the relatively large amount of peat that burned. Additional CH_4 was emitted by the large fires in Indonesia during late-1997. *Levine* [1999] used estimates of the area burned, separated it into sub-areas by vegetation type, and estimated a possible range of CH_4 emission of 1.2 to 3.7 Tg CH_4 with a most likely value of 1.8 Tg CH_4. So, biomass burning, particularly in boreal regions, likely made a small contribution to the anomalous CH_4 increase during 1998.

Other CH_4 budget terms may have contributed to the observed increase in 1998. For example, methane is emitted from rice agriculture through the same mechanisms involved in natural

Table 2. Temperature and Precipitation Anomalies for Wetland Regions Relative to 1980-1999

	30-90°N*		Equator-30°N		Equator-30°S	
Year	Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
	(°C)	(mm d^{-1})	(°C)	(mm d^{-1})	(°C)	(mm d^{-1})
1998	0.26 (41%)	0.28 (100%)	0.49 (100%)	-0.28 (-100%)	0.28 (100%)	0.05 (15%)
1999	-0.17 (-20%)	-0.09 (-28%)	-0.12 (-46%)	-0.04 (-13%)	-0.29 (-100%)	0.21 (59%)

*HNH temperature and precipitation anomalies are for May-October; tropical anomalies are annual. Percentages in parentheses are relative to largest anomaly during 1980-1999.

Table 3. Methane Emission Anomalies from Natural Wetlands Relative to 1982-1993 by Semihemisphere Calculated With the Model

	Model Emission Anomaly (Tg CH_4)		
Year	30-90°N	Equator-30°N	Equator-30°S
1998	+11.6	+1.5	+11.5
1999	-7.9	-5.7	-4.2

wetland emissions. About 90% of rice field area (and production) is in the northern tropics; a large increase in this source is inconsistent with the CH_4 measurements that showed a relatively small increase in that latitude zone. Methane emission rates from rice agriculture are sensitive to temperature [*Khalil et al.*, 1998], so this source probably made a small contribution to the observed increase. Clathrates are also not a likely significant contributor. Destabilization of clathrates occurs in ocean sediments, but the CH_4 released is oxidized in the oxic layer at the interface with the atmosphere [*Kvenvolden*, 1999].

Reaction of CH_4 with hydroxyl radical (OH) in the troposphere is about 90% of the total CH_4 sink, and it is the largest term in the global methane budget. The temperature anomalies observed during 1998 have the potential to affect the magnitude of this term. The rate coefficient for the reaction increases by ~2% for each 1°C increase. Also, assuming constant relative humidity, atmospheric [H_2O] could have increased with higher tropospheric temperatures, thereby increasing [OH]. In addition, during 1998 a negative global anomaly in stratospheric O_3 was observed [*Hamilton and Fan*, 2000]. Lower stratospheric O_3 by itself would lead to increased tropospheric OH. A larger chemical sink due to higher temperatures and more tropospheric OH, and with no other changes to the CH_4 budget, would have lowered CH_4 growth rates, opposite to what was observed.

4. Summary and Conclusions

The globally averaged methane growth rate increased from an average of 3.9 ppb yr^{-1} during 1995-1997 to 12.7 ppb yr^{-1} in 1998. This change in growth rate implies an increase in the imbalance between sources and sinks equal to 24 Tg CH_4 during 1998 relative to the previous 3 years. During 1999 the global increase was 2.6 ppb, but CH_4 decreased by 1.6 ppb in the northern hemisphere. This suggests that the 1998 increase is not a return to the large growth rates observed during the late-1970s and early-1980s. The spatial and seasonal distributions of the anomalous increase are indicators of the sources that contributed. Based on latitude zones comprising 25% of the atmosphere, the largest increases during 1998 were at 30-90°N and 0-30°S. Model calculations suggest there were increased CH_4 emissions from wetlands, contributing an additional 11.5 Tg CH_4 in the HNH and 13 Tg CH_4 in the tropics (30°S-30°N), because of a warmer and wetter environment in wetland regions. Large boreal fires, particularly in Siberia, may have also contributed perhaps 5.7 Tg CH_4. Though our model estimates of wetland emission anomalies are likely overestimated, a clear link between CH_4 emissions and climate exists. If in the future, natural wetland regions trend towards warmer wetter environments than they are currently, CH_4 emissions from this source will increase.

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